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The research supported by this grant is directed towards gaining an understanding how the auditory system processes complex sounds. The results of binaural psychophysical experiments in human subjects suggest (1) that spectrally synthetic binaural processing is the rule when the number of components in the tone complex are relatively few (less than 10) and there are no dynamic binaural cues to aid segregation of the target from the background, and (2) that waveforms having large effective envelope depths are on the average more easily lateralized than those having small effective envelope depths. Psychophysical experiments in human subjects using sinusoidally amplitude modulated narrowband noises and complex patterns of modulation of tonal carriers have been directed toward understanding auditory object perception. Results from experiments and theoretical modelling suggest that slow temporal modulation of different spectral components can be used by the auditory system to fuse these components into one auditory image. The results of psychophysical experiments show that the effects of noise bandwidth on intensity discrimination of noise in chinchillas are similar to data from human subjects; the results can be accounted for by a modification of the ideal energy detector. Neurophysiological experiments have been directed at gaining an understanding of how auditory neurons encode pitch related information in the temporal properties of discharge. The results show that a temporal representation at the level of the cochlear nucleus can account for some, but not of the pitches of rippled noise.															
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Auditory Processing of Complex Sounds Across Frequency Channels (AFOSR-89-0335)

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The Effect of Envelope Power on the Ability to Lateralize 3-Tone Complexes on the Basis of Interaural Envelope Delays.

Raymond H. Dye, Mark Stellmark and Andrew Niemiec

The goal of this study was to assess the viability of envelope detection as the front-end of high-frequency binaural processors. Interaural delay between envelopes of high-frequency carriers is a potent cue for lateralizing stimuli presented through head phones, and it was our hope to characterize the envelope extraction stage by presenting waveforms whose effective envelopes were manipulated without altering the spectrum of the signals. This was accomplished by manipulating the starting phases of 3 component signals such that the starting phases were all 0 degrees, 0-45-0 degrees, or 0-90-0 degrees. The effective envelopes of these waveforms are maximal when all starting phases are the same and minimal when the starting phases are 0-90-0. To characterize the effective envelope of these waveforms, the standard deviation of the instantaneous power in units of average power were computed (defined as z). To the extent that envelopes are extracted by passing waveforms through a nonlinearity (half-wave rectifier or square-law device) followed by a low-pass filter, then one should expect that waveforms of higher z should be more easily lateralized.

Threshold interaural envelope delays were measured in a 2-AFC task as a function of frequency spacing (Δf = 25, 50, 100, and 200 Hz) with the carrier frequency (f_c) set to 4000 Hz. The level of each component was 50 dB SPL, and the signal duration was 200 ms with 10-ms linear rise/decay times. For comparison, thresholds were also measured for SAM 4000-Hz tones with reduced depths of modulation so that the effects of decreasing modulation depth and decreasing envelope power could be directly compared.

Reducing envelope power had only a negligible effect on threshold interaural envelope delays for Δf s of 200 and 100 Hz but a large and systematic effect at 50 Hz and especially at 25 Hz. For three of the five observers the 0°-90°-0°, Δf = 25 Hz condition was so difficult that 75% correct could not be reached with delays as large as 2000 μ s.

In order to determine whether envelope manipulations brought about by other means would produce similar effects on lateralization performance, threshold interaural envelope delays were measured for SAM 4000-Hz tones that were either 100% modulated, 70% modulated, or 35% modulated. The 70% and 35% modulated waveforms have z 's that are equal to those of the 0-45-0 and 0-90-0 conditions respectively. To compare performance between SAM and equal amplitude components, some decision had to be reached regarding the effective modulation rate of the complexes generated from equal amplitude components. For 0-90-0, the modulation frequency is twice the frequency spacing, but the fact that the intermediate temporal lobes for 0-45-0 and 0-0-0 are relatively small leads to ambiguity regarding the effective modulation frequency. In comparing 100% AM and the 0-0-0 condition, the agreement is good if one treats the effective modulation frequency of the equal amplitude complexes as twice the frequency spacing. For comparisons between 0-45-0 and 0-90-0 with 70% and 35% amplitude modulation waveforms, the agreement is good if one compares waveforms having the same frequency spacing, indicating that the secondary

lobes in the temporal waveforms of the 0-45-0 and 0-90-0 waveforms do not double the effective modulation rate. In general, the results obtained are consistent with binaural cross-correlation of the outputs of envelope detectors.

Discrimination of Interaural Envelope Delays: The Effect of Randomizing Component Starting Phase.

Raymond H. Dye, Andrew Niemiec and Mark Stellmack

The goal of this study was to examine the nature of envelope extraction in the discrimination of high-frequency waveforms on the basis of envelope delay. Threshold interaural envelope delays were measured for 3- and 5-component complexes for which the starting phases of all components were either 0° or randomized between intervals of a 2-AFC task. The carrier frequency was 4 kHz and the modulation frequency was varied from 25 to 500 Hz. The results showed that thresholds were greater for the phase-randomized conditions than the 0-phase conditions. The phase effect tended to diminish with increasing modulation frequency for 3-component complexes but not for the 5-component complexes. Sensitivity to envelope delay was better for 5-component complexes than for 3-component complexes at most modulation frequencies. In general, the results showed superior lateralization performance for conditions in which the envelope fluctuations were greater, a finding that is consistent with models of high-frequency binaural processing that include envelope extraction prior to binaural comparison.

Lateralization of Narrowband Noise on the Basis of Envelope Delay as a Function of Envelope Power.

Raymond H. Dye

A study was undertaken to ascertain the extent to which envelope power could account for the lateralizability of narrow bands of noise. Threshold interaural envelope delays were measured in a 2-AFC task for narrow bands of noise whose center frequency was fixed at 4000 Hz. The bandwidth of the noise was set to 50, 100, or 200 Hz. All components of the noise were equal amplitude, and different noise samples were generated by randomizing the starting phases of the components. For this study the waveforms were classified by into five ranges of z-values and efforts were made to correlate performance with z. Data were gathered using blocked trials (all 100 trials in a run employing waveforms within the same range of z's) and mixed trials (all range of z's run in a 100-trial block). While performance with high effective envelope depths was superior to that with low envelope depths on the average, it appears that relationship between z and threshold envelope delays is not simple. This is especially true of the data gathered with a 50-Hz wide band of noise. Part of the problem concerns the fact that the location of the major peak in the temporal waveform varies from one waveform to the next when the bandwidths are relatively narrow. Waveforms with early peaks appear to be

easier to lateralize than those with later peaks. As such, the data gathered at a single restricted range of z -values tend to be quite variable. We are currently examining signal generation schemes that will allow us to generate waveforms of variable effective envelope depth without altering the location of the prominent peak in the temporal waveform. Although factors other than effective envelope depth (as measured by z) are important for the sensitivity of observers to envelope delays, it is clearly the case that some sort of envelope extraction mechanism precedes the derivation of envelope delay by the binaural auditory system via cross-correlation.

Detection of Interaural Envelope Delays in High-Frequency Targets Presented Amongst Diotic Distractors.

Raymond H. Dye

A study was undertaken that sought to gain insight into the processes by which multiple high-frequency carriers are lateralized when they are amplitude modulated. Of special interest were potential differences in performance when the target carrier (the component that was sinusoidally amplitude-modulated such that the envelope presented to the left ear led the one that was presented to the right ear) and neighboring carriers were modulated at the same (200 Hz) versus when the distractors were modulated at a rate different from that of the carrier. The interaurally delayed component ("target") was a 3000-Hz-carrier, 100% amplitude-modulated by a 200-Hz sinusoid. The distractors were additional carriers that were 100% amplitude-modulated at 25, 50, 100, 200, or 400 Hz. The number of distractors was fixed at two, and the spacing between the distractors and the target (Δf) was varied from 500 to 1500 Hz. For comparison, threshold delays were measured for amplitude modulated 3000-Hz targets presented in isolation. The signals were 200 ms in duration, gated with 10 ms rise-decay times, with the distractors and the target gated simultaneously at the two ears. A two-interval task was used such that the first interval always presented a diotic 3000-Hz carrier modulated at 200 Hz and the second interval presented all three carriers. On half of the trials, the modulated 3000-Hz target was interaurally delayed (to the right channel) during the second interval; otherwise it was diotic (as were the distractors).

In addition to assessing the performance of subjects, they were interrogated regarding the listening strategies employed on a particular run of trials. The subjects' reports indicate that (1) targets and distractors that are modulated at the same frequency tend to be perceptually fused such that the entire complex sounds shifted during dichotic presentations, even though only the 3000-Hz carrier is delayed, (2) the detection of delays presented when the distractors and targets are modulated at different rates is accomplished by "hearing out" the target when it is delayed during the second interval as long as the frequency separation between the target and distractors is at least 1000 Hz, (3) the target and distractors are often perceptually fused, forming single intracranial events, when the target and distractors are separated by only 500 Hz even though the modulation frequencies of the target and distractors might differ (25 Hz vs. 200 Hz). In

many of these cases under (3), the task can be accomplished either by hearing out the delayed component or fusing the complex.

Objective psychophysical measures of performance show that sensitivity is quite good for conditions in which the distractors and target are spectrally remote and modulated at different rates, with performance approaching what is found for targets presented in isolation. When the target and distractors are modulated at the same rate, significant binaural interference is observed regardless of the frequency separation between targets and distractors; the presence of distractors elevates thresholds by a factor of 2-3. When targets and distractors are within 1000 Hz of one another and they are modulated at different rates, sensitivity to envelope delays can be especially poor, with some subjects requiring 5-8 times larger delays when the distractors are present than when they are absent.

Detection and Recognition of Amplitude Modulation with Tonal Carriers.

Stanley Sheft and William Yost

The ability of listeners to process multiple sources of sinusoidal amplitude modulation (AM) was evaluated using both detection and recognition procedures. For all conditions, the stimulus was a two-tone (909 and 4186 Hz) complex. Test-AM frequencies were 4 and 17 Hz. In the detection paradigm, d-primes obtained with simultaneous modulation of both tones were compared to the d-primes obtained with modulation of just one of the tonal components. When both tones were modulated at the same frequency, a phase disparity between the envelopes reduced AM detectability. With the envelopes in phase, results showed a linear summation of the d-primes for the individual components. With modulation of the two tones at different AM frequencies, performance approximated optimal processing of two sources of uncorrelated information. A similar result was obtained in the recognition paradigm when the task was to discriminate between the two modulation frequencies. When the AM frequency was fixed and the task was to identify which carrier was modulated, performance was near chance. Results are consistent with processing of near-threshold AM through modulation-specific channels that are broadly tuned to carrier frequency.

Spectral Fusion Based on Coherence of Amplitude Modulation.

Stanley Sheft and William Yost

The ability of listeners to attend to a subset of components (the target) of a tonal complex was investigated using a forced-choice procedure. The stimulus was an eight-component tonal complex. The components of the target subset ($n = 1, 2, \text{ or } 3$ components) were distinguished from the complex by coherent amplitude modulation (AM). Each trial of the cued 2IFC task was preceded by a presentation of the coherently modulated target components in isolation. For each interval of a trial, either the target or an equal number of non-target components shared the coherent AM. Subjects were required to

detect the interval in which the target components were coherently modulated. The remaining components of the complex were all either modulated at different rates, modulated with a random shift of the target-modulator phase angle, or not modulated. Performance was measured as a function of the number of target components, the harmonic relationship among the target components, and the harmonic relationship between the target and non-target spectral groups. With coherent AM of harmonic target components, the increment in d' with increasing n exceeded predictions based on the combination of independent sources of information, suggesting that these stimuli may be processed as an entity by the auditory system.

Temporal Integration in Amplitude Modulation Detection.

Stanley Sheft and William Yost

Thresholds for detecting sinusoidal amplitude modulation (AM) of a wideband noise carrier were measured as a function of the duration of the modulating signal. The carrier was either (a) gated with a duration that exceeded the duration of modulation by the combined stimulus rise and fall times; (b) presented with a fixed duration that included a 500-ms carrier fringe preceding the onset of modulation; or (c) on continuously. In condition (a), the gated-carrier temporal modulation transfer functions (TMTFs) exhibited a bandpass characteristic. For AM frequencies above the individual subject's TMTF highpass segment, the mean slope of the integration functions was -7.46 dB per log unit duration. For the fringe and continuous-carrier conditions (b and c), the mean slopes of the integration functions were respectively -9.30 and -9.36 dB per log unit duration. Simulations based on integration of the output of an envelope detector approximate the results from the gated-carrier conditions. The more rapid rates of integration obtained in the fringe and continuous-carrier conditions may be due to "over-integration" where at brief modulation durations portions of the unmodulated carrier envelope are included in the integration of modulating signal energy.

Cued Envelope-Correlation Detection.

Stanley Sheft and William Yost

Involvement of envelope coherence in source segregation requires that listeners can both detect the coherence and then in some manner selectively process the various fluctuation patterns that characterize the different sources. Envelope coherence or synchrony detection was therefore evaluated in masking and discrimination conditions requiring selective cross-spectral processing of similar patterns of envelope fluctuation.

If a spectral subset of a complex sound first precedes the sound, the subset will tend to be heard as a separate auditory image when repeated as part of the complex. A cued 2IFC test procedure was used to encourage this type of spectral segregation; each trial was preceded by presentation of the synchronous target noise bands as a cue complex. Center frequencies (CFs) of

the two to three target bands were either 500, 1250, or 3125 Hz, with bandwidth ranging from 12.5-200 Hz. Stimulus duration was 400 ms.

In contrast to previous studies of synchrony detection that used a conventional (uncued) procedure, results from the cued procedure indicated relatively small effects of noise bandwidth and of the frequency separation between noise bands. In the discrimination conditions, envelope coherence in the nonsignal observation interval also had little effect on performance. In the masking conditions, the task was to detect coherence among target noise bands in the presence of masker noise bands. Target and masker bands shared a common bandwidth. Though performance was impaired by the maskers, there was less masking than generally observed when modulated maskers are used in experiments evaluating sinusoidal modulation detection, and depth and rate discrimination. When more than one masking band was present, there was little effect of coherence among the masking bands of the nonsignal interval if these bands were asynchronous with the target bands of the cue complex. With masker coherence, the task then requires synchrony detection restricted to the spectral region of the target bands.

Across conditions, spectral location of the target bands tended to have little effect on synchrony-detection performance, especially at narrowest bandwidths. This is consistent with the type of wideband processing needed for sound-source segregation. Results from the masking and discrimination conditions indicate that along with detecting cross-spectral synchrony, the auditory system can with fairly good precision selectively process similar concurrent patterns of envelope fluctuation.

Detection of Intensity Decrements Followed by Increments.

Stanley Sheft and William Yost

Data were collected from a modified decrement detection procedure in order to compare subject performance to the predictions of two decision statistics derived from the output of an envelope detector. At roughly the midpoint of each stimulus presentation, there was an intensity increment of the gated wideband noise carrier. The task was to detect an intensity decrement just preceding the increment in the signal interval of the 2IFC task. Decrement duration ranged from 2.5 to 40 ms. Increments of 3, 6, and 9 dB were used with the onset of the increment randomly occurring 150-300 ms from the stimulus onset. Decrement detection was also measured for conditions in which there was no increment. Best performance was obtained with the 3-dB increment. With the 6- or 9-dB increment, thresholds were significantly higher and showed less change as a function of decrement duration. Simulations based on the output of an envelope detector used either the variance or the ratio of the largest-to-smallest value as the decision statistic. For both statistics, simulations approximated subject performance in the conditions with no increment. Simulations, however, did not show the drop in performance with the 6- or 9-dB increment, suggesting involvement of multiplicative internal noise in envelope detection.

The Effect of Intensity Increments on Decrement Detection.

Stanley Sheft and William Yost

A previous study [S. Sheft and W.A. Yost, J. Acoust. Soc. Am. 89, 1913 (1991)] indicated that decrement detection thresholds are affected by sudden level changes unrelated to the decrement. The present study measured the time course of the effect of an intensity increment (pedestal) on decrement detection with wideband noise. In one set of conditions, the increment followed the decrement with the temporal separation between the decrement offset and the increment onset varying between 0-80 ms. In another set, the decrement occurred within the pedestal with the decrement onset 0-160 ms from the pedestal onset. Increment size ranged from 3-12 dB. Compared to thresholds obtained without the increment, the effect of the increment depended on the temporal separation between both the stimulus and pedestal onsets and the decrement onset. With brief separations, performance improved across all increment levels. Consistent with interference due to the neural onset response, the introduction of a silent gap before the pedestal eliminated the beneficial effect of the increment. However, the effect of the increment extended out to 160 ms, past possible involvement of the neural onset response and short-term adaptation.

Modulation Detection Interference with Complex Modulators.

Stanley Sheft and William Yost

Amplitude modulation (AM) masking has been a topic of concern in recent studies of complex sound processing. Previous work with sinusoidal modulators has shown that even with the masker and probe carriers widely separated in frequency, masker modulation can significantly interfere with detection of probe modulation. To evaluate the effect of complex stimulus modulation on cross-spectral processing of AM, a two-tone complex was used as the masker modulator in the present study. Experimental conditions involved either detection of probe modulation or discrimination of the pattern of probe modulation.

Similar to results obtained with sinusoidal masker modulators, there was a detrimental effect of masker modulation on the processing of probe modulation. Unlike results from CMR studies, adding modulated masker components never led to a reduction in the amount of masking. Interference was also obtained when the probe was modulated at the beat rate of the two-tone masker modulator. The amount of interference due to beating of the masker modulator diminished with increasing either the probe AM rate or the masker-modulator beat rate from 4 to 10 Hz. These results indicate a masking effect not predicted by a Fourier representation of the stimulus envelope. Results will be discussed in terms of the possible involvement of the cross-spectral processing of AM in sound-source determination.

Spectral Transposition of Envelope Modulation.

Stanley Sheft and William Yost

Previous work [Sheft and Yost, *J. Acoust. Soc. Am.* 85 Suppl. 1, S121 (1989)] has shown that it is often difficult to identify which component of a multicomponent complex is amplitude modulated. The role of the carrier in envelope processing was examined in the present study with a cued 2IFC envelope-discrimination procedure. The narrowband noises of the two observation intervals differed only in terms of their pattern of envelope fluctuation, with the signal interval a repetition of the cue envelope pattern at a center frequency (CF) different from that of the cue. Cross-spectral transposition of envelope information was evaluated by varying the number of common CFs between the noise bands of the cue complex and the target bands of the observation intervals. With both the cue and observation intervals consisting of a single noise band, the ability to transpose envelope information from the cue to the observation-interval CF diminished with increasing noise bandwidth from 12.5 to 200 Hz. Results from the multi-band conditions indicate that listeners are unable to integrate the envelope information across audio-frequency regions to improve performance. In fact, the added noise bands led to a significant drop in performance in many conditions. These results suggest that envelope information is not processed independent of the spectral location of the modulated carrier.

Temporal Representation of Rippled Noise in the Anteroventral Cochlear Nucleus of the Chinchilla.

William Shofner

These neurophysiological experiments have been directed at gaining an understanding of how auditory neurons encode stimulus information found in the time domain of complex sounds, particularly those complex sounds which can generate the perception of pitch. Information in the time domain can be found in the waveform fine structure and envelope. Rippled noise is a broadband stimulus which produces the perception of pitch, yet is aperiodic in the time domain. Cos+ rippled noise is generated when a broadband noise is delayed and then added to the undelayed noise. The resulting stimulus has a power spectrum that varies in a cosinusoidal fashion in which the peaks are separated by $1/\tau$, where τ is the delay. The autocorrelation function of waveform fine structure of cos+ noise has a single peak at the delay of the noise. Thus, unlike wideband noise which is aperiodic and has a flat autocorrelation function, rippled noise is an aperiodic stimulus that does not have a flat autocorrelation function. Moreover, the autocorrelation function of the envelope of cos+ noise also has a single peak at the delay. Cos- noise is generated when the delayed version of the noise is subtracted from the undelayed noise; the autocorrelation function of the waveform fine structure of cos- noise shows a null at the delay, while the autocorrelation function of the envelope of cos- noise shows a single peak at the delay. Comparison of responses to cos+ and cos- noise will provide data as to whether neurons

extract the delay from the waveform fine structure or from the envelope.

Neurophysiological experiments investigated the temporal responses of cochlear nucleus neurons in the chinchilla to rippled noises. In some instances, responses to tones complexes were also obtained. These temporal response properties are those based on the time intervals between individual spikes and were evaluated by constructing renewal densities. Renewal densities have been referred to as the autocorrelation function of the spike train and are constructed by summing the distributions of first-order and all higher-order interspike intervals. The renewal density shows the probability of discharge following an action potential; that is, the renewal density shows the average firing pattern following a spike.

In general, all physiological neuronal types recorded can show periodicities in their discharge in response to tone complexes that are related to the fundamental frequency of the complex. However, only those neurons that show phase-locking at best frequency have renewal densities that show a major peak at the delay in response to $\cos+$ rippled noise; these neurons show a null at the delay in renewal densities in response to $\cos-$ rippled noise. Thus, neurons which show phase-locking to best frequency tones extract the delay of rippled noise from the waveform fine structure of the stimulus. Most cochlear nucleus units which did not show phase-locking to best frequency tones gave renewal densities that did not contain features related to the delay of rippled noise. A few of these non-phase-locked units did show peaks in renewal densities at the delay for both $\cos+$ and $\cos-$ rippled noises, suggesting that these units extract the delay from the stimulus envelope.

The strength of synchrony in response to rippled noise was quantified from the renewal density as the root-mean-squared deviation in firing rate around the delay normalized to the average firing rate. This analysis confirmed that the units that show the strongest synchrony at the rippled noise delay are low-best frequency, phase-locked units.

Synchrony at the rippled noise delay was also demonstrated using evoked potential recording. Autocorrelation functions of the neurophonic potential showed peaks at the delay for both $\cos+$ and $\cos-$ rippled noises. This observation suggests that the neurophonic potential reflects temporal properties of the stimulus envelope, primarily because of the low-pass filtering properties of the recording electrode. The finding that the neurophonic reflects the stimulus envelope is consistent with the frequency following response recorded with scalp electrodes in human subjects. In addition, peaks could be observed in autocorrelation functions of neurophonic potentials with delays as short as 1 ms; peaks were never observed in renewal densities of single units for rippled noise delays as short as 1 ms.

The results demonstrate that a temporal representation of the delay of rippled noise does exist at the level of the cochlear nucleus; this temporal representation found at the single unit level can account for some, but not all of the pitches of rippled noise. To account for all pitches, it may be necessary to combine the outputs of several frequency channels.

Increment Detection of Wideband and Bandlimited Noises by Chinchillas.

William Shofner, William Yost and Stanley Sheft

Many studies have addressed the effect of noise bandwidth on intensity discrimination in humans, and these studies all generally agree that intensity discrimination thresholds decrease as the bandwidth of the noise increases. As the bandwidth narrows, there is an increase in the temporal fluctuations of the instantaneous power in the noise waveform, and these fluctuations presumably interfere with a listener's ability to detect an increment in intensity. Green (1960, J. Acoust. Soc. Am., 32, 121-131) derived an analytical model for intensity discrimination of noise for an ideal energy detector which measures the power in two noise samples and selects the waveform with the largest power. The ideal energy detector model is described as

$$d' = (WT)^{\frac{1}{2}} \frac{S}{N} \frac{1}{[1 + \frac{S}{N} + \frac{1}{2} (\frac{S}{N})^2]^{\frac{1}{2}}} \quad (1)$$

where d' is the detectability, W is bandwidth, T is signal duration (or integration time), S is the signal power and N is the noise power. Note that S/N is equivalent to the Weber fraction $\Delta I/I$. This model takes into account the increase in temporal fluctuations as the noise bandwidth narrows. The equation of the energy detector model can be rearranged to give

$$10 \log \left(\frac{S}{N} \frac{1}{[1 + (\frac{S}{N}) + \frac{1}{2} (\frac{S}{N})^2]^{\frac{1}{2}}} \right) = 10 \log \frac{d'}{T^{\frac{1}{2}}} - 5 \log W \quad (2)$$

Equation 2 is a linear equation having a slope of -5 dB/decade increase in bandwidth; that is, the ideal energy detector model predicts that a 10-fold increase in the noise bandwidth will result in a decrease in threshold of -5 dB. The reported degree of the bandwidth effect does vary among studies in human subjects and is typically less than the predicted -5 dB/decade slope of the ideal energy detector model.

The present study examined the intensity discrimination capabilities of the chinchilla for noise signals. Six (5 male and 1 female) binaural, adult chinchillas (*Chinchilla lanigera*) served as subjects. Chinchillas were trained to hold down a response lever with a reward chute and release the lever in the presence of a 1 s increment in noise level. Increments were generated by adding the noise coherently during the 1 s signal interval. Animals initiated a trial by pressing down on the response lever, and the 1 s signal interval varied randomly from 1-8 s after the animal initiated a trial. Thresholds were obtained using a two-down, one-up tracking rule, and the animals received food pellet rewards for correct responses. Thresholds were obtained as signal to standard ratios in dB and were converted to DL or $\Delta I/I$.

The Difference Limens (DLs) as a function of the overall level of the continuous masker for wideband noise were obtained. The range of levels

tested was limited to 42-82 dB SPL. The lowest level at 42 dB SPL approaches the noise floor of the sound attenuating chamber. Levels above 82 dB SPL were not presented in order to avoid causing any cochlear damage to the animals. For the average chinchilla, there is a decrease in threshold from 4.520 dB, which then appears to be relatively constant between 52-82 dB SPL. The average DL over the range of 52-82 dB SPL is 1.334 dB. An analysis of variance (ANOVA) was carried out on the signal re: standard ratios for the average chinchilla for the levels between 52-82 dB SPL. The ANOVA confirmed that the average increment detection thresholds are equal at base levels of 52, 62, 72 and 82 dB SPL ($F=1.887$; $F < F_{0.05(1),3,20}$; $p > 0.05$). Thus, Weber's Law appears to hold for the average chinchilla over the range of levels from 52-82 dB SPL for the wideband noise.

Increment detection thresholds were obtained as a function of bandwidth for a continuous masker noise of 72 dB SPL. Bandwidths used were wider than the bandwidths of individual auditory filters; thus, for a given bandwidth, the output across several frequency channels must be combined. The linear regression through the data has a slope of -3.6 dB/decade increase in bandwidth for the average chinchilla. The Y-intercept of this regression line is 5.9 and is equal to $10\log(d'/T^{1/2})$ from Equation 2. The empirical thresholds for the average chinchilla fall above those predicted by the ideal energy detector model. The bandwidth slopes obtained from individual animals ranged between -2.6 to -4.4.

These results demonstrate that for conditions of a continuous masker and where the masker and signal have the same bandwidth, there is a decrease in increment detection threshold as bandwidth increases. While the slopes of the bandwidth function obtained for the chinchilla are less than the predicted slope of the ideal energy detector model, the bandwidth slopes obtained for the chinchilla are similar to those generally reported for humans which are also shallower than -5 (see P.N. Schacknow and D.H. Raab, 1976, J. Acoust. Soc. Am., 60, 893-905).

What Hearing Really Is: Auditory Image Perception and Analysis.

William A. Yost

The evolution of hearing has culminated in the human's remarkable ability to determine the sources of sounds. Sound source identification appears to be the motivation for the evolution of an auditory system. A century of psychoacoustical research has revealed a wealth of information about processing the basic properties of sound. However, far less attention has been paid to how the auditory system uses this information to determine sound sources. Psychoacoustical data, models, and theories suggest that the human's ability to spectrally resolved components of a complex sound and their ability to localize sounds are responsible for sound source identification. Sound sources provide a number of other characteristics that could be used by an auditory system to aid it in sound source identification. A highly evolved auditory system should be able to use these characteristics to help form auditory images of sound sources. One such characteristic or variable is the slow temporal modulation of sound generated by almost all sound sources.

Consider for instance, the slow frequency vibrato and amplitude jitter present in all voiced utterances. We argue that the human auditory system uses such slow temporal modulations to identify sound sources. Processing these modulations has certain consequences for auditory perception of complex sounds. As a consequence of processing temporal modulation, the auditory system appears to group together tonal components that share a common pattern of temporal modulation even when the tonal components are widely spaced in frequency. These effects help establish the relevance of slow temporal modulation for sound source identification.

Temporal Modulation Transfer Functions for Pure Tones.

William A. Yost and Stanley Sheft

Temporal Modulation Transfer Functions (TMTFs) were obtained for sinusoidally amplitude modulated (SAM) pure tones. TMTFs were obtained by determining the depth of SAM required for modulation detection in a two-alternative, forced-choice adaptive procedure. TMTFs were obtained for 500-Hz, 1000-Hz, and 4000-Hz carrier frequencies; for durations of 125 ms and 500 ms (all stimuli were shaped with a 20-ms raised cosine); in gated and continuous background conditions; and for modulation rates ranging from 2 to 128 Hz. In the gated condition, the carrier tone was gated on and off and the modulation occurred over the full duration of the tone, while in the continuous condition, the carrier tone was on continuously and it was modulated only during the observation interval. Thresholds for modulation detection were lower in the continuous than in the gated condition and the thresholds were lower for the 500-ms than for the 125-ms stimuli. The TMTFs displayed a bandpass characteristic in all conditions, but the highpass segment was steeper for the gated than for the continuous conditions. The loss in sensitivity at low modulation frequencies meant that the lowest thresholds were obtained for modulation frequencies of 4-Hz to 8-Hz in the continuous condition and above 16 Hz in the gated condition.

Auditory Image Perception and Amplitude Modulation: Frequency and Intensity Discrimination of Individual Components for Amplitude-Modulated Two-Tone Complexes.

William A. Yost

Auditory image perception describes the auditory processing of sound sources, especially in complex, multi-source acoustic environments. A number of investigators have shown that slow temporal modulation imparted to a subset of target components in a multi-tone complex sound will cause the target components to fuse into an auditory image. As such, coherent slow temporal modulation may be one of the cues used by the auditory system to form auditory images, and these images would in turn allow for the identification of sound sources. We also discovered an apparent consequence of the auditory system's use of coherent slow temporal modulation to form auditory images. When

sinusoidal amplitude modulation is used to modulate a two-tone complex consisting of two tonal carriers of very different frequencies, listeners have great difficulty in processing the temporal modulation pattern of either of the two constituent carrier-tones, even when they are separated by as many as five octaves. That is, despite the fact that the carriers are separated by many critical bands, a listener's ability to (1) detect the presence of modulation, (2) discriminate a change in modulation rate, and (3) discriminate a change in modulation depth of either tone is severely impaired when both tones are modulated at the same rate. We have called this form of interference Modulation Detection Interference (MDI) in that the processing of modulation in one frequency channel is interfered with when the same pattern of modulation is present in another frequency channel. The investigators surmised that MDI results from the auditory system using the coherent amplitude modulation in the two channels to fuse the two carriers into a single auditory image. Because temporal modulation was the cue used to fuse the tones into one auditory image, the auditory system has difficulty processing the temporal modulation of either of the two constituent tones of that image.

The present study addresses the ability of the auditory system to process other dimensions of the tonal complexes when the two tones are modulated and MDI occurs. In particular, when a two-tone complex is amplitude modulated and listeners have difficulty processing the modulation pattern of either tone (i.e., MDI occurs), are the thresholds for discriminating: 1) a change in the frequency of one of the tonal carriers, 2) a change in the overall amplitude of one of the amplitude modulated complexes increased because of the common pattern of modulation? Because temporal modulation, but neither frequency nor overall amplitude, were used by the auditory system to form an auditory image, it is predicted that neither frequency nor intensity discrimination would be affected when the two carrier tones are modulated and MDI occurs.

Modulation Detection Interference for Discriminating Modulation Depth of Sinusoidally Amplitude Modulated Tones.

William A. Yost

The ability of listeners to discriminate a change in the depth of sinusoidal amplitude modulation (SAM) of a 4000-Hz tone was measured using the MDI (Modulation Detection Interference) procedure (see Yost, Sheft, and Opie, JASA, Vol. 86, 1989, p. 2138-2147). Modulation depth discrimination was measured for base depths of 0, 25, 50, and 100% depth of modulation and for rates of SAM ranging from 2 to 128 Hz. To a first approximation, thresholds for discriminating a change in SAM depth were 3-5% of the base depth, except at low-modulation rates (below 8 Hz) where thresholds were slightly higher. When a 1000-Hz tone modulated at the same rate as the 4000-Hz tone was presented simultaneously with the 4000-Hz tone, thresholds for modulation depth discrimination increased to 10-15% of the base depth. No such increases in thresholds were observed when the 1000-Hz tone was not modulated. Thus, as for tasks involving detection of SAM or discriminating a change in SAM rate (see Yost, Sheft, and Opie, JASA, Vol. 86, 1989, p. 2138-2147), the presence of another modulated tone severely disrupts the temporal processing of the

target sound, even when the two sounds are many critical bands apart. These results appear consistent with the assumption that slow temporal modulation may be used to form auditory images.

Recognition Memory for Arbitrary, Complex Waveforms.

William A. Yost

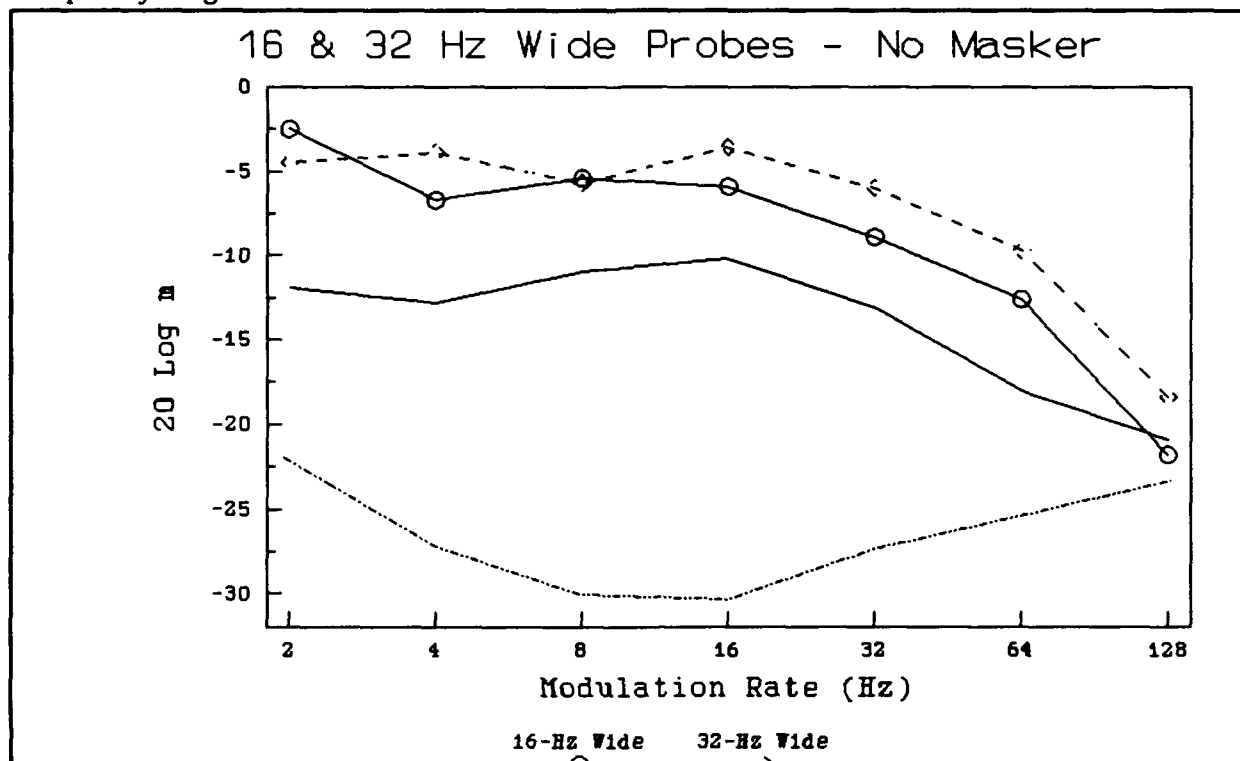
Recognition memory for arbitrary complex stimuli was measured using the operating characteristic technique developed by Egan [J.P. Egan, AFCRC TN 58-51, AD 152650 (1958)]. Ten complex stimuli (500 ms in duration), each consisting of six, randomly chosen, equal amplitude sinusoidal components spanning frequencies from 300 to 3000 Hz were used as a training set. After 15 minutes of listening to the training set, listeners were presented a 20-stimulus test set consisting of the ten training stimuli along with ten additional complex stimuli (generated in the same way as the ten training stimuli). In a recognition memory paradigm, listeners used a five-point rating scale to rate their confidence that a stimulus presented from the test set was from the training set. Different constraints were placed on the selection of the complex waveforms to determine how those constraints affected recognition memory. For one condition there were no constraints except as described above; for a second condition the six-tonal components were harmonics (randomly chosen) of a common fundamental; and for a third condition the six-tone complex was sinusoidally amplitude modulated at rates of 4, 16, or 32 Hz. The results showed that the method can be used to study processing of complex sounds and that amplitude modulation enhances the ability of listeners to remember arbitrary complex sounds.

Processing Temporal Modulation of Narrow-Band Noises.

William A. Yost and Stanley Sheft

The ability of listeners to detect sinusoidal amplitude modulation of probe signals was measured in a number of conditions. The probes were 500 ms in duration and were either a 4000-Hz tone or narrow bands of noise centered at 4000 Hz with bandwidths ranging from 16 Hz to 1024 Hz. Thresholds for probe modulation were determined when a masker, consisting of narrow-band noises centered at 1000 Hz with bandwidths ranging from 32 Hz to 1024 Hz, was simultaneously presented with the probe. Thresholds for probe modulation were also obtained when there was no masker. The rates of sinusoidal amplitude modulation of the probes (and in some cases of the maskers) ranged from 2 Hz to 128 Hz. Thresholds were obtained from five listeners in a two-alternative, forced-choice adaptive psychophysical task. When the bandwidth of the noise was less than approximately 512 Hz, modulation detection thresholds were higher than those obtained for tonal signals and noises whose bandwidths were greater than 512 Hz. The results from the various conditions are consistent with the assumption that slow temporal modulations inherent in narrow-band noises interfere with the ability of listeners to detect low rates

of sinusoidal amplitude modulation. Such interference exists even when the masker is two octaves away from the probe. The results are consistent with the recent literature involving temporal processing of signals across wide frequency regions.



A New Psychophysical Procedure for Measuring Selective Attention.

William A. Yost, Raymond H. Dye, Mark Stellmack and Stanley Sheft

Recently a number of new psychophysical procedures have been proposed to measure and account for subjects performance in multi-dimensional stimulus paradigms. These procedures involve stimulus contexts in which listeners are presented more than one stimulus dimension on any experimental trial and are asked to make a binary response concerning the stimulus presentation. These methods are an extension of the earlier signal-detection work that accounted for subjects performance in multiple observation-interval tasks. These newer procedures are being developed because of the renewed interest in auditory perception of complex sounds. This work describes a procedure designed for conditions in which the listener receives two stimuli per observation interval, one the target and the other the non-target (or distractor stimulus). Each stimulus varies along the same continuum and the listener judges, with a binary response, which of two target possibilities occurred.

The procedure is a simplified variation of the General Recognition Theory of Ashby and Townsend.

A number of simple assumptions underlie this procedure: t represents the target and d the distractor or non-target, t_i and d_j are, then, the various values of the two stimuli along a continuum. We assume that $i = j = -m \leq i, j \leq m$; that is, the stimulus variation along the continuum is the same for each dimension and the stimulus variation is symmetrical about some midpoint (i.e. $i, j = 0$). On any trial $t_i + d_j$ is presented and the listener is to determine whether t_i on that trial belongs to one of two classes, P (positive class) or N (negative class). For instance, t and d could be two different frequencies (d a low-frequency tone and t a high-frequency tone) and the continuum could be the interaural time difference for each tone. Thus, on every trial both tones are simultaneously presented each with a randomly chosen value of an interaural time difference. Half of the possible time delays would favor the right ear and half would favor the left ear. The listener decides if the high-frequency tone (t) is left (N) or right (P) of midline. Thus, the range of possible interaural time differences are the same for both tones and the interaural time differences are chosen to be symmetric about 0 (midline). Note that if i and j vary from $-m$ to m , there are $(2m+1)^2$ trials in the experiment, and each combination of t_i and d_j is presented once with the listener deciding for each presentation whether t_i belonged to class N or P . Thus, the entries in the response matrix are either P s (in the example, right responses) or N s (left responses).

This procedure would be used when one is interested in how a listener processes one stimulus in the presence of another stimulus, especially when the values of each stimulus are super-threshold. That is, how much attention or weight is given to the d dimension when listeners are asked to attend to or process the t dimension? A number of vocabularies have been used to describe such processing. One can describe the task in terms of selective or divided attention, or in terms of whether or not the listener is analytic or synthetic in his or her ability to process the target dimension, or in how well the listener can "hear out" the target in the presence of the distractor. In many complex stimulus task one stimulus stands out (e.g. forms a stream or an image or an object or a scene from the background of other stimuli, and the investigator wants to determine the extent to which this stimulus is perceptually separable from the other stimulus or stimuli.

Thus, a crucial performance measure is the weight (w , with $0 \leq w \leq 1$) assigned to the distractor or d dimension. In order to determine w , we make the assumption that each cell in the decision matrix (C_{ij}) is given a value by:

$$C_{ij} = v_i + (w * v_j), \quad 1)$$

where v_i and v_j are the values associated with each stimulus variable such that $-v_m \leq v_i, v_j \leq v_m$ and $v_i = f(t_i)$ and $v_j = f(d_j)$ with the function $f()$ being monotonic; and w ($0 \leq w \leq 1$) is the relative weight given to the d dimension.

The Decision Rule is:

respond P , iff $C_{ij} > b$;
respond N , iff $C_{ij} < b$;

guess, iff $C_{ij} = b$, where $-((w*v_m)+v_m) \leq b \leq ((w*v_m)+v_m)$. 2)

The constant b is a bias the listener might have for responding P (or N). Therefore, the response space is divided into the P and N areas when $C_{ij} = b$, or by the line:

$$v_i + (w*v_j) = b; v_i = -w*v_j + b. \quad 3)$$

The slope of the straight line in the decision matrix determines the weight, w , and the intercept of the line determines the bias, b . In order to construct a response matrix (an ideal response matrix in this case) an Assignment Rule is used such that a value of 1 is assigned to a P response, -1 to a N response, and the rows and columns of the matrix are determined by i and j , with $-m \leq i, j \leq m$ (i.e. $v_i = i$ and $v_j = j$). The resulting response matrix (with cells R_{ij} assigned a value of 1 or -1) can be generated in which the line $(i - wj + b)$ is the best fitting line as defined by equation 3). The slope of this line determines, w , the relative weight assigned to the d dimension and the intercept, b , determines the listener's bias. The best fitting line can be determined from a response matrix in one of two ways (both are equivalent for the ideal response matrix defined above as explained below).

One rule includes the fact that the best fitting line occurs when the sum of the C_{ij} s corresponding to the P response (all positive C_{ij} s) minus the sum of the C_{ij} s corresponding to the N response (all negative C_{ij} s) is maximal, that is:

$$\text{when } \sum_{i=-m}^m \sum_{j=-m}^m P - \sum_{i=-m}^m \sum_{j=-m}^m N \text{ is maximum.} \quad 4)$$

Thus, the straight line which maximizes equation 4) can be determined from real data in order to determine the slope (weight) and intercept (bias). Alternatively a least squares criterion may be used. That is, one can find that straight line which provides the best least-squares fit to the data as defined by minimizing the sum of the squared deviations between the line and the deviate responses. In order to determine how well this process might work for data that could be obtained in a real experiment, we used a Monte Carlo technique to evaluate the procedure and the outcomes showed that the technique is very robust usually taking a single block of trials to yield a reliable estimate of the slope and intercept of the best fitting line as defined above.

The approach for obtaining an estimate of w and b is essentially distribution-free with only a few assumptions being required. The method could be adopted to a model of how listeners might assign values to the cells in the decision space, and a similar approach to the one outlined above could be derived to evaluate the model. A number of statistics can be obtained to evaluate how good the best fitting line (as defined by equation 3) is to the response matrix; for instance, 1) the percent of N and P responses successfully divided into two classes by the line or 2) the sum of the squared deviations of the deviate responses from the line. An interesting aspect of

the approach is the ability to make the distractor the target and the target the distractor and to repeat the procedure as a means of testing the symmetry of the measures obtained. Also note that the stimulus values (t_i and d_j) are supra-threshold, allowing one to explore a large stimulus space.

Measuring Modulation Detection Interference With a New Procedure.

William A. Yost

The new procedure for measuring selective attention described elsewhere in this report was used to measure depth of modulation processing in a modulation detection interference (MDI) paradigm. Listeners were asked to indicate whether a 500-ms target tone (4000-Hz carrier) which was sinusoidally amplitude modulated (SAM) at 16 Hz had a larger or smaller depth of modulation than a standard SAM tone presented as a cue before each trial. The standard (cue) was modulated with a depth of modulation of -15 dB and the target stimulus was modulated with depths of modulation of -7.5, -9, -10.5, -12, -13.5, -16.5, -18, -19.5, -21 dB (i.e. half with depths greater than -15 dB and half with depths less than -15 dB). The ability to make this depth discrimination judgment was obtained in the three basic MDI conditions: Target Alone (TA) condition in which only the target was presented, Unmodulated Distractor (UD) condition in which a 1000-Hz tone was presented simultaneously with the target, and the Modulated Distractor (MD) condition in which the distractor was also amplitude modulated with the same depths of modulation as the target. The rates of SAM for the distractor were either the same as the target, 16 Hz, or different, 8 or 32 Hz. For three of the listeners their weights for the distractor dimension estimated from the best fitting line to the response matrix as defined for the new procedure for measuring selective attention were all 0.0 for the TA condition and 0.0, 0.0, and 0.1 for the UD condition, and then rose to 0.9, 1.1, and 0.6 for the MD condition when the distractor and target were modulated at the same rate (16 Hz). These results are consistent with the general MDI finding in that listeners are analytic in the PT and UD conditions but synthetic when the distractor and target are modulated together at the same rate in the MD condition. The fourth listener had a weight of 0.0 in the PT condition but weights of greater than 1 for the UD condition (3.3) and the MD condition (2.6), indicating that in these conditions she was using the depth of modulation of the distractor and not the target despite the fact that feedback was provided on each trial consistent with target modulation depth. She was behaving somewhat analytic (3.3 is like a 0.3 weight and 2.6 is like a 0.4 weight) but she was responding as if she could not hear the target (she could hear it since she performed as the other listeners did in the TA condition, but when both the distractor and target were present she responded as if she was largely ignoring the target). Thus, the new procedure allows for a robust metric for determining individual differences based on the concept of how listeners assign weights to the distractor dimension. All listeners became more analytic (weights toward 0.0) when the distractor was modulated at a different rate than the target: at 8 Hz the weights were 0.1, 0.3, 0.0, 0.2 and at 32 Hz they were 0.0, 0.2, 0.0., and 0.3. The bias of the listeners was always with ± 1 , indicating very little

AFOSR-89-0335

response bias by these listeners. Again these results are consistent with the description of listener performance in modulation detection or discrimination in MDI paradigms. The new selective attention paradigm allows for a description of performance that is more valid in terms of describing how listeners hear out targets in the presence of distractors and the procedure captures individual differences in a more meaningful manner than measures of thresholds obtained in the traditional MDI procedures.

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